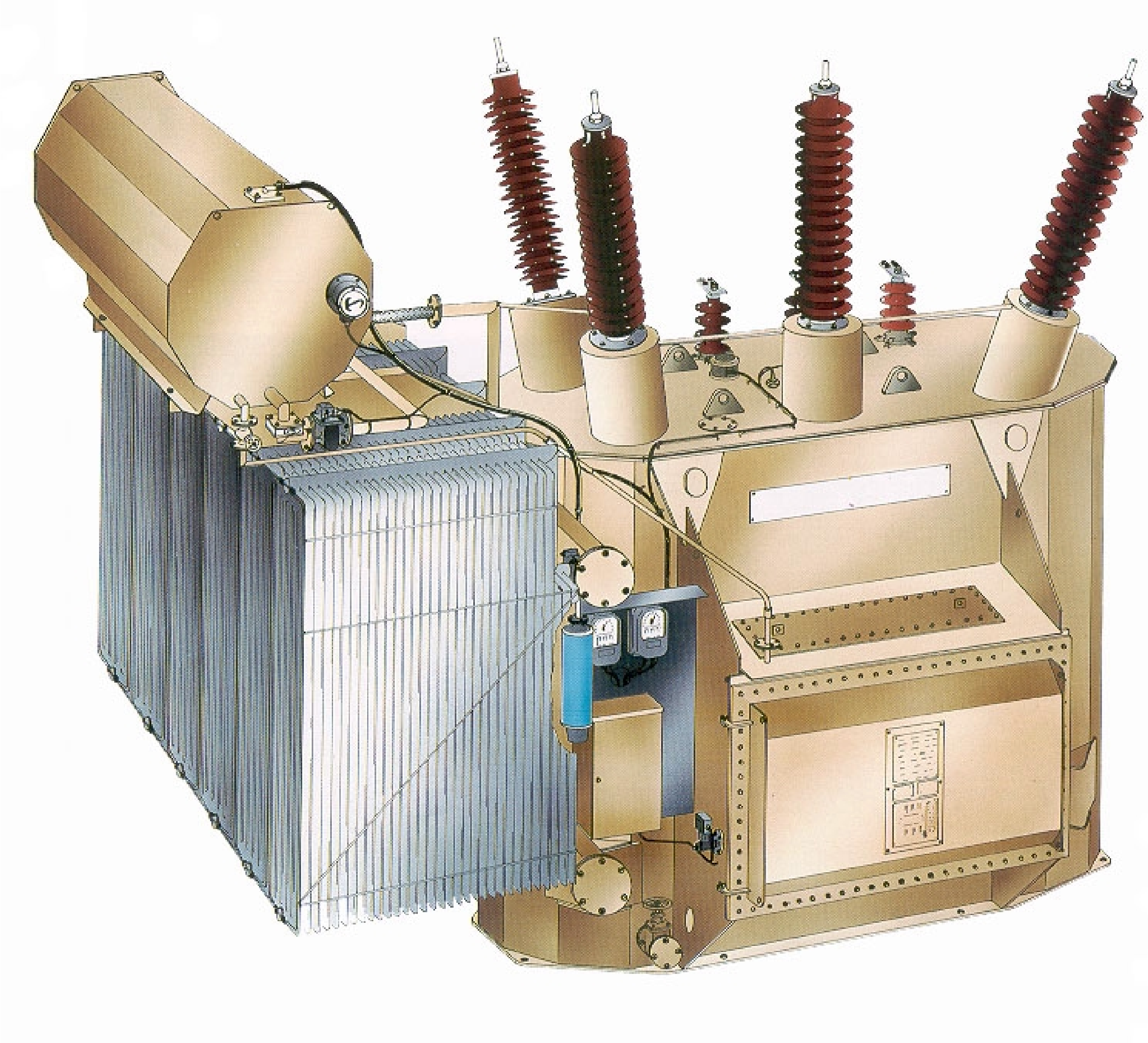
TESTING OF POWER TRANSFORMERS



KT 80 GB 2000-01
ABB Oy
Power transformer

TESTING POWER TRANSFORMERS

Test procedures and equipment used for the testing of large power transformers at ABB Oy, Power transformer, Vaasa Works are dealt with in the following sections. The measuring equipment differens from those explained herein. The priciples of routine, type and special tests are however similar and thus this booklet is applicable for testing of distribution transformers too.

The electrical characteristics and dielectric strenght of the transformers are checked by means of measurements and tests defined by standards.

The tests are carried out in accordance with IEC Standard 76, Power Transformers, unless otherwise specified in the contract documents.

Contents

1. SUMMARY OF DIELECTRIC TESTS

According to the Standard IEC 76-3 the dielectric test requirements for a transformer winding depend on the highest voltage for equipment U_m applicape to the winding and on whether the winding insulation is uniform or non-uniform.

Category of winding	Highest voltage Um/kV	Lightning impulse (LI) (see clause 13 and 14)	Switching impulse (SI) (see clause 15)	Long duration AC (ACLD)	Short duration AC (ACSD)	Separate source AC
Uniform insulation	Um ≤ 72,5	Type (note 1)	Not applicable	Not applicable (note 1)	Routine	Routine
Uniform and non-uniform insulation	72,5<Um≤170	Routine	Not applicable	Special	Routine	Routine
	170<Um<300	Routine	Routine (note 2)	Routine	Special (note 2)	Routine
	Um≥300	Routine	Routine	Routine	Special	Routine

NOTE 1 In some countries, for transformers with Um ≤ 72,5 kV, LI tests are required as routine tests, and ACLD tests are required as routine or type tests.
NOTE 2 If the ACSD test is specified, the SI test is not required. This should be clearly stated in the enquiry document

2. MEASUREMENT OF VOLTAGE RATIO AND CHECK OF CONNECTION SYMBOL

Purpose of the measurement

The voltage ratio of the transformer is the ratio of voltages (in three-phase transformers line-to-line voltages) at no-load, e.g., 110000 V/10500 V.

The purpose of the measurement is to check that the deviation of the voltage ratio from the specified value does not exceed the limit given in the relevant transformer standard (generally 0,5 %).

The connection symbol of the transformer is checked at the same time.

Performance and results of the measurement

The voltage ratio measurements are carried out by means of a voltage ratio measuring bridge; the error of the bridge is less than ± 0.1 %. The supply voltage is 220 V a.c. The fuctions of the bridge is shown in Fig. 2-1. The voltages of the transformer to be checked are compared to the corresponding voltages of the regulating transformer, which is provided with a decade display unit and located in the gridge casing. When the bridge is balanced, the voltage ratio of the decade transformer is equal to that of the transformer unded test. The result can be seen directly from the numeral display of the bridge.

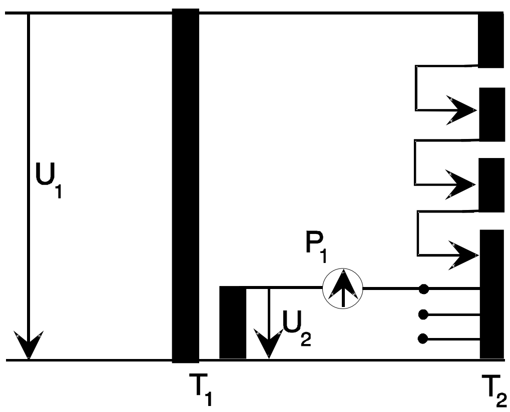


Fig. 2-1.

Bridge measurement (of the voltage ratio)

T_1 transformer to be measured
T_2 regulating transformer equipped with a decade display, P_1 zero-sequence voltmeter, U_1 supply voltage of the bridge, U_2 secondary voltage of the transformer.

Since the measuring device is a single-phase bridge, the voltage ratio of a pair of windings mounted on the same leg is measured at a time. It is to be observed that the ratio indicated by the bridge does not alvays correspond to the ratio of the line-to-line voltages. The result depends on the connection symbol of the transformer. For each winding connected to the bridge it is important to observe whether the number of turns relates to the line-to-line or line-to-neutral voltage. For example,

the voltage ratio of a 120/21 kV Yd-connecter transformer is $120000:\frac{\sqrt{3}}{21000}$ V = 3.299. The reading obtained from the bridge is to be compared to this value.

The connection symbol of the transformer is checked in conjunction with the voltage ratio measurement. When the measuring leads from the transformer

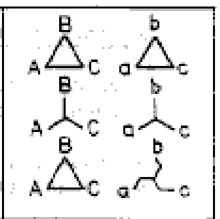
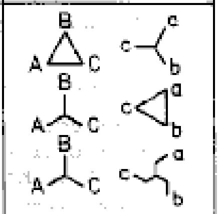
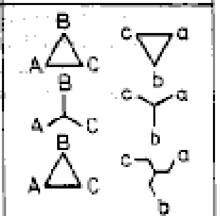
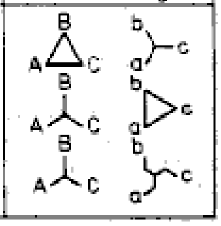
are connected to the bridge according to the relevant vector diagram in Table 2-2, the bridge can be balanced only if the transformer connection is correct.

The voltage ratios are measured for each tapping connection of the transformer. In the report the specified tapping voltage ratios are stated, as well as the measured ratios and their deviations from the specified ratios.

<u>Table 2-2</u>

Determination of the connection symbol

Clock hour figure (left), connection symbol (middle) and vector diagram (right).

0	Dd 0 Yy 0 Dz 0	
5	Dy 5 Yd 5 Yy 5	
6	Dd 6 Yy 6 Dz 6	
11	Dý 11 Yd 11 Yz 11	

3. Measurement of the winding resistances

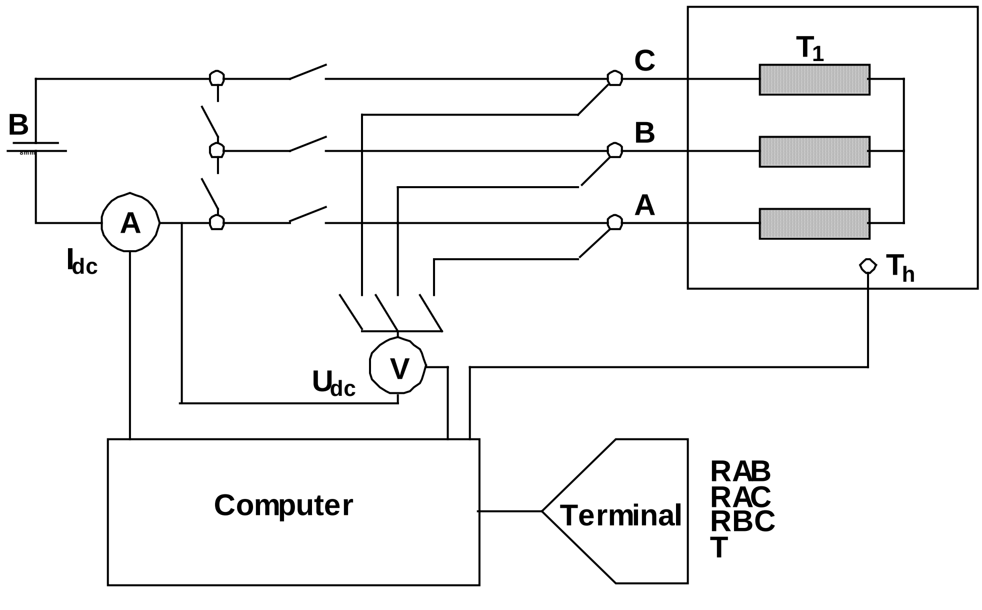
Purpose of the measurement

The resistance between all pairs of phase terminals of each transformer winding are measured using direct current. Furthermore the corresponding winding temperature is measured.

The measured resistances are needed in connection with the load loss measurement when the load losses are corrected to correspond to the reference temperature. The resistance measurement will also show whether the winding joints are in order and the windings correctly connected.

Apparatus and basic measuring circuit

The measurement is performed by TETTEX 2285 transformer test system.



kuva1

Fig. 1.1-1 Circuit for resistance measurement
T_1 = transformer under test, A = ammeter, U = voltmeter
B = DC-supply, T_h = thermometer.

The principle of the measurement is as follows:
The voltage drop U_{dc} caused by the direct current Idc an by the resistance RAB, RAC and RBC is measured.The resistances are then calculated from U_{dc} and I_{dc} using correction for the error caused by the internal resistance of the voltage measuring equipment

The temperature is measured from oil filled thermometer pockets situated in the transformer cover by means of an electronic thermometer connected to the computer.

Test report

The resistance values and the average temperature are calculated. In the report the terminals, between which the resistances are measured, the connection, the tapping position and the average temperature of the windings during the measurement are stated.

4. MEASUREMENT OF IMPEDANCE VOLTAGE AND LOAD LOSS

Purpose of the measurement

The measurement is carried out to determine the load-losses of the transformer and the impedanse voltage at rated frequency and rated current. The measurements are made separetely for each winding pair (e.g., the pairs 1-2, 1-3 and 2-3 for a three-winding transformer), and furthermore on the principal and extreme tappings.

Apparatus and measuring circuit

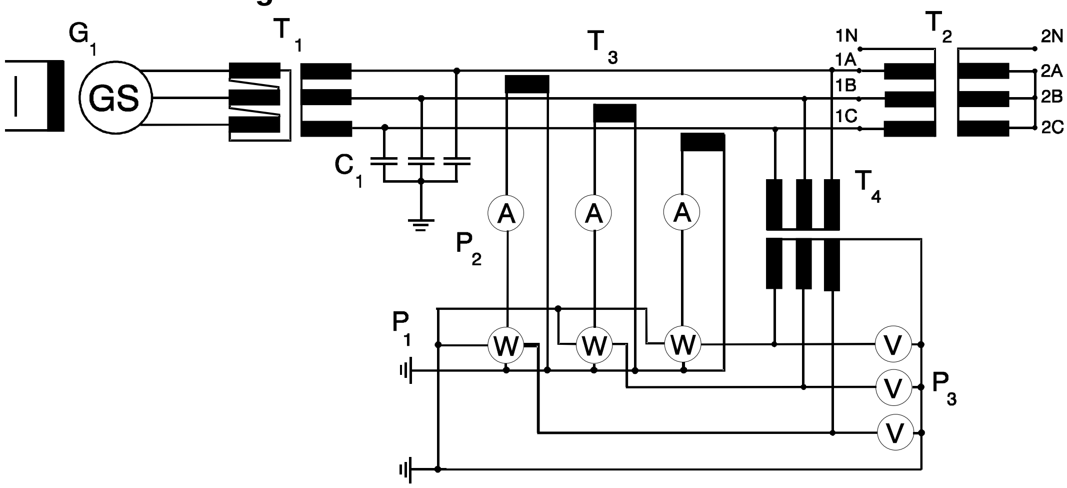


Fig. 4-1 Circuit for the impedance and load-loss measurement.
G_1 supply generator, T_1 step-up transformer. T_2 transformer to be tested, T_3 current transformers. T_4 voltage transformers. P_1 wattmeters, P_2 ammeters (r.m.s. value), P_3 voltmeters (r.m.s. value) C_1 capacitor bank.

The supply and measuring facilities are described in a separate measuring apparatus list (Section 20).

Current is generally supplied to the h.v. winding and the l.v. winding is short-circuited.

Performance of the measurement

If the reactive power supplied by the generator G_1 is not sufficient when measuring large transformers, a capasitor bank C_1 is used to compensate part of the inductive reactive power taken by the transformer T_2.The voltage of the supply generator is raised until the current has attained the required value (25...100 % of the rated current according to the standard 4.1). In order to increase the accuracy of readings will be taken at several current values near

the required level. If a winding in the pair to be measured is equipped with an off-circuit or on-load tap-changer. the measurements are carried out on the principal and extreme tappings. The readings have to be taken as quickly as possible, because the windings tend to warm up due to the current and the loss values obtained in the measurement are accordingly too high.

It the transformer has more than two windings all winding pairs are measured separately.

Results

Corrections caused by the instrument transformers are made to the measured current, voltage and power values. The power value correction caused by the phase displacement is calculated as follows:

(4.1) $$P_c = P_e * (\frac{\delta_u - \delta_i}{3440} * \tan\varphi) = P_e * (1 + \frac{K}{100})$$

P_c = corrected power
P_e = power read from the meters
δ_u = phase displacement of the voltage transformer in minutes
δ_i = phase displacement of the current transformer in minutes
φ = phase angle between current and voltage in the measurement (φ is positive at inductive load)
K = correction

The correction K obtained from equation (4.1) is shown as a set of curves in Fig. 4-2.

The corrections caused by the instrument transformers are made separatley for each phase, because different phases may have different power factors and the phase displacements of the instrument transformers are generally different.

If the measuring current I_m deviates from the rated current I_N, the power P_{km} and the voltage U_{km} at rated current are obtained by applying corrections to the values P_c and U_c relating to the measuring current. The corrections are made as follows:

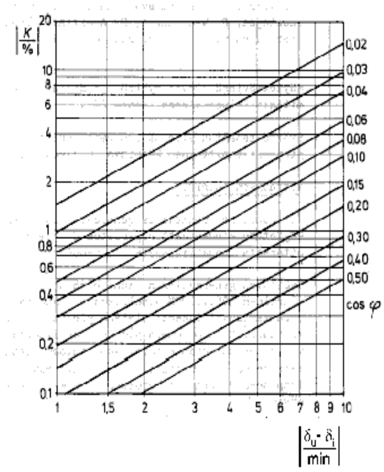
(4.2) (4.2) $$P_{km} = \left(\frac{I_N}{I_m}\right)^2 * P_c$$

(4.3) $$U_{km} = \frac{I_N}{I_m} * U_c$$

Fig. 4.2

The correction caused by the phase displacement of istrument transformers.

K correction in percent, δ_u - δ_i phase displacement in minutes. cosδ power factor of the measurement. The sign of K is the same as that of δ_u - δ_i.



Mean values are calculated of the values corrected to the rated current and the mean values are used in the following. According to the standards the measured value of the losses shall be corrected to a winding temperature of 75 °C (80 °C, if the oil circulation is forced and directed). The transformer is at ambient temperature when the measurements are carried out. and the loss values are corrected to the reference temperature 75 °C accordint to the standards as follows.

The d.c. losses P_{Om} at the measuring temperature ϑ_m are calculated using the resistance values R_{1m} and R_{2m} obtained in the resistance measurement (for windings 1 and 2 between line terminals):

(4.4) $$P_{Om} = 1.5 * (I_{1N}^2 * R_{1m} + I_{2N}^2 * R_{2m})$$

The additional losses P_{am} at the measuring temperature are

(4.5) $$P_{am} = P_{km} - P_{Om}$$

Here P_{km} is the measured power, to which the corrections caused by the instrument transformer have been made, and which is corrected to the rated current according to Equation (4.2)

The short-circuit impedance Z_{km} and resistance R_{km} at the measureing temperature are

(4.6) $$Z_{km} = 100 * \frac{U_{km}}{U_N} \%$$

(4.7) $$R_{km} = 100 * \frac{P_{km}}{S_N} \%$$

U_{km} is the measured short-circuit voltage corrected according to Equation (4.3); U_N is the rated voltage and S_N the rated power. The short circuit reactance X_k does not depend on the losses and X_k is the same at the measuring temperature (ϑ_m) and the reference temperature (75 °C), hence

(4.8) $$X_{km} = \sqrt{Z_{km}^2 - R_{km}^2} = X_{kc}$$

When the losses are corrected to 75 °C, it is assumed that d.c. losses vary directly with resistance and the additional losses inversely with resistance. The losses corrected to 75 °C are obtained as follows:

(4.9) $$P_{kc} = P_{Om} * \frac{\vartheta_s + 75^o C}{\vartheta_s + \vartheta_m} + P_{am} * \frac{\vartheta_s + \vartheta_m}{\vartheta_s + 75^o C}$$

ϑ_s = 235 °C for Copper
ϑ_s = 225 °C for Aluminium

Now the short circuit resistance R_{kc} and the short circuit impedance Z_{kc} at the reference temperature can be determined:

(4.10) $$R_{kc} = 100 * \frac{P_{kc}}{S_N} \%$$

(4.11) $$Z_{kc} = \sqrt{X_{kc}^2 + R_{kc}^2}.$$

Results

The report indicates for each winding pair the power S_N and the following values corrected to 75 °C and relating to the principal and extreme tappings.

- d.c. losses P_{Oc} (PDC)
- additional losses P_{ac} (PA)
- load losses P_{kc} (PK)
- short circuit resistance R_{kc} (RK)
- short circuit reaactance X_{kc} (XK)
- short circuit impedance Z_{kc} (ZK)

Literature

(4.1) IEC Publ. 76-1 (1993) Power Transformers.

5. MEASUREMENT OF NO-LOAD LOSS AND CURRENT

Purpose of the measurement

In the no-load measurement the no-load losses P_O and the no-load current I_O of the transformer are determined at rated voltage and rated frequency. The test is usually carried out at several voltages below and above the rated voltage U_N, and the results are interpolated to correspond to the voltage values from 90 to 115 % of U_N at 5 % intervals.

The asymmetric voltage at the neutral terminal is also measured in certain cases. The harmonics on the no-load current are also measured on request.

Apparatus and measuring circuit

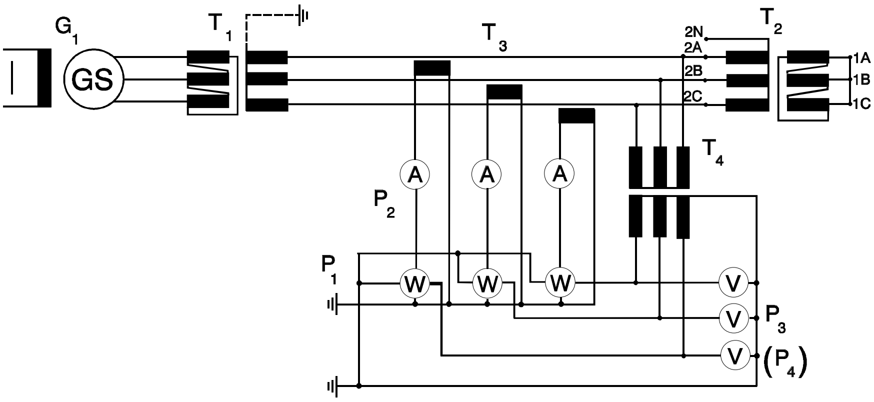


Fig. 5-1. Circuit for the no-load measurement.
G_1 supply generator, T_1 step-up transformer. T_2 transformer to be tested, T_3 current transformers, T_4 voltage transformers, P_1 wattmeters, P_2 ammeters, P_3 voltmeters (r.m.s. value), P_4 voltmeters (mean value x 1.11).

The available supply and measuring facilities are described in a separrate measuring instrument list (Section 20).

Performance

The following losses occur at no-load

- iron losses in the transformer core and other constructional parts
- Dielectric losses in the insulations
- load losses caused by the no-load current

While the two last mentioned losses are small, they are generally ignored.

The following formula is valid for the iron losses

(5.1) $$P_0 = k_1 * f * \left(\frac{U'}{f}\right)^2 + k_2 * U^2$$

P_O = measured iron losses
k_1 = coefficient relating to hysteresis losses
k_2 = coefficient relating to eddy-current losses
f = frequency
U' = mean value of voltage x 1.11 (reading of a rectifier voltmeter

scaled to read the r.m.s. value of a sinusoidal voltage)
U = r.m.s. value of the voltage

When carrying out the no-load measurement, the voltage wave shape may somewhat differ from the sinusoidal form. This is caused by the harmonics in the magnetizing current which cause additional voltage drops in the impedances of the supply. The readings of the mean value meter and r.m.s. meter will be defferent.

Because the losses are to be determined under standard conditions, it is necessary to apply a wave shape correction whereby the losses are corrected to correspond to test conditions where the supply voltage is sinusoidal.

In the test the voltage is adjusted so that the mean value voltmeter indicates the requider voltage value. Then the hysteresis losses correspond to standard conditions, but the eddy-current losses must be correcred. From (5.1).

(5.2) $$P_0 = \frac{P_{on}}{100} * (p_1 + k * p_2)$$

(5.3) $$k = \left(\frac{U}{U'}\right)^2$$

P_{on} = losses at sinusoidal voltage under standard conditions
p_1 = ratio, expressed as a precentage, of hysteresis losses to total iron losses
p_2 = ratio, expressed as a percentage, of eddy-current losses to total iron losses

The loss value corresponding to standard conditions is obtained from the measured value P_O as follows:

(5.4) $$P_{on} = P_0 * \frac{100}{p_1 + k * p_2}$$

It is assumed that for oriented sheets $p_1 = p_2 = 50$ %

The current and power readings of different phases are usually different (the power can even be negative in some phase). This is due to the asymmetric construction of the 3-phase transformer; the mutual inductances between different phases are not equal.

Results

The report shows the corrected readings at each voltage value, as well as the mean values of the currents of all three phases.
A regression analysis is carried out on the corrected readings. From the no-load curve thus obtained no-load losses and no-load apparent power corresponding to voltage values from 90 to 115 % of U_N at 5 % intervals are determined and stated. Furthermore the no-load current in percentage on the rated current is stated.

6. INDUCED AC VOLTAGE TEST (ACSD)

Purpose of the test

The object of the test is to secure that the insulation between the phase windings, turns, coils, tapping leads and terminals, for non-uniformly insulated windings also the insulation between these parts and earth, withstand the temporary overvoltages and switching overvoltages to which the transformer may be subjected during its lifetime.

Performance

The excitation voltage is applied to the terminals of the low-voltage winding. The other windings are left open-circuited. The machines and the equipment are described in the test equipment list (Section 20).

The tapping of the off-circuit or on-load tap-changer is chosen so that in all windings the voltage during the test is as near as possible the rated test voltage.

The test frequency is either 165 Hz or 250 Hz. The duration of the test is

$$\frac{\text{rated frequency}}{\text{test frequency}} * 120\ s$$

The test is successful if no collapse of the test voltage occurs.

<u>a. Short duration induced AC withstand test for Uniformly insulated HV-windings</u>

The test voltage connection is essentially the same as in service. A three-phase winding is tested with symmetrical three-phase voltages induced in the phase windings. If the winding has a neutral terminal, it is eaerthed during the test.

The test voltage is twice the rated voltage. However, the voltage developed between line terminals of any winding shall not exceed the rated short duration power-frequency withstand voltage.

The voltage is measured from terminals to earth or between terminals of the low voltage winding using voltage transformers. Alternatively the capasitive taps of the bushings on the high voltage side are used for voltage measurement. The voltage is so adjusted, that the average of the voltage values measured from terminals to earth or between terminals is equal to the required test voltage value. The partial discharges shall be measured if not otherwise agreed.

b. Short duration induced AC withstand test for non-uniformly insulated HV-windings

For three-phase transformers, two sets of tests are required

a) A phase-to earth test with rated withstand voltages between phase and earth according to standard with partial discharge measurement.
b) A phase-to-phase test with earthed neutral and with rated withstand voltages between phases according to standard with partial discharge measurement.

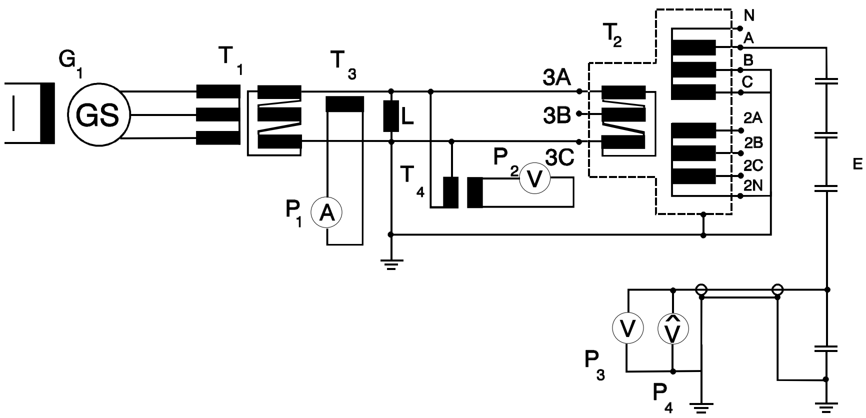


Fig. 6-1. Test circuit for induced overvoltage withstand test on non-uniformly insulated winding of three-phase transformer.
G_1 supply generator, T_1 step-up transformer, T_2 transformer understest, T_3 current transformer,
T_4 voltage transformer, L compensating reactor, E voltage divider, P_1 ammeter, P_2 voltmeter, P_3 voltmeter, (r.m.s. value) P_4 voltmeter (speak value).

The test connection shown in Fig. 6-1 is applicable to three-phase transformers if the insultaion level of the neutral terminal is at least one third of the insulation level of the terminals. The test voltage is applied to the individual phases in succession. During each application the test voltage from terminal to earth is equal to the rated withstand voltage.

The voltage is measured with a capacitive voltage divider in conjunction with voltmeters responsive to peak and r.m.s. values. The peak voltmeter indicates the peak value divided by $\sqrt{2}$. The test voltage is adjusted according to this voltmeter.

Test report

The test voltage, frequency, test duration and tapping are stated in the report.

7. SEPARATE-SOURCE VOLTAGE WITHSTAND TEST

Purpose of the test

The object of the test is to secure that the insulation between the windings and the insulation between windings and earthed parts, withstand the temporary overvoltages and switching overvoltages which may occur in service.

Test circuit

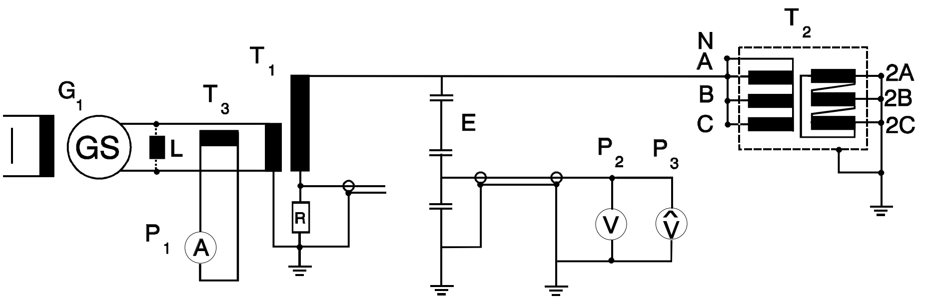


Fig. 7-1 Test circuit for separate-source voltage withstand test.
G_1 supply generator, T_1 test transformer, T_2 transformer under test, T_3 current transformer, L compensating reaaactor, E voltage divider, P_1 ammeter, P_2 voltmeter (r.m.s value) P_3 voltmeter (peak value).

The voltage is measured using a capacitive voltage divider in conjunction with voltmeters responsive to r.m.s. and peak values. The peak-voltmeter indicates the peak value divided by $\sqrt{2}$. The test voltage is adjusted accordin to this meter.

The generators and the equipment are described in the test equipment list (Section 20).

Performanse

The test is made with single-phase voltage of rated frequency. The test voltage is applied for 60 seconds between the winding under test and all terminals of the remaining windings, core and tank of the transormer, connected together to earth (Fif. 7-1).

The test is successful if no collapse of the test voltage occurs.

The line terminals of non-uniformly insulated windings are tested by induced test according to Section 6.b.

Test report

The test voltage, frequency and test duration are stated in the report.

8. OPERATION TEST ON ON-LOAD TAP-CHANGER

After the tap-changer is fully assembled on the transformer, the following tests are performed at (with exception of b) 100 % of the rated auxiliary supply voltage:

a) 8 complete operating cycle with the transformer not energized

b) 1 complete operating cycle with the transformer not energized, with 85 % of the rated auxiliary supply voltage

c) 1 complete operating cycle with the transformer energized and rated voltage and frequency at no load

d) 10 tap-change operations with ± 2 steps on either side of the principal tapping with as far as possible the rated current of the transformer, with one winding short-circuited.

9. LIGHTNING IMPULSE TEST

Purpose of the test

The purpose of the impulse voltage test is to secure that the transformer insultations withstand the lightning overvoltages which may occur in service.

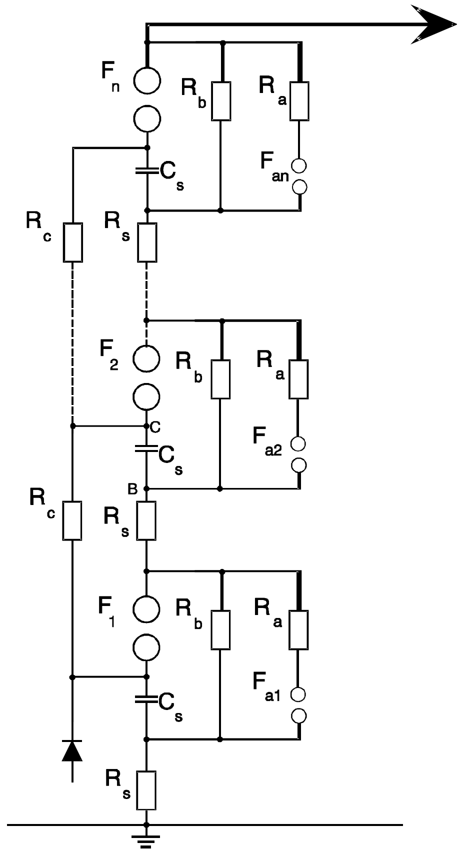
Testing equipment

Impulse generator

Fig. 15-1

Basic circuit diagram
of the impulse generator.

C_1 impulse capacitor
R_c charging resistor
R_s series resistor
R_a low-ohmic discharging
 resistor for switching impulse,
R_b high-ohmic discharging resistor
 for switching impulse
F_1...F_n main spark-gaps,
F_{al}...F_{an} auxiliary spark-gaps

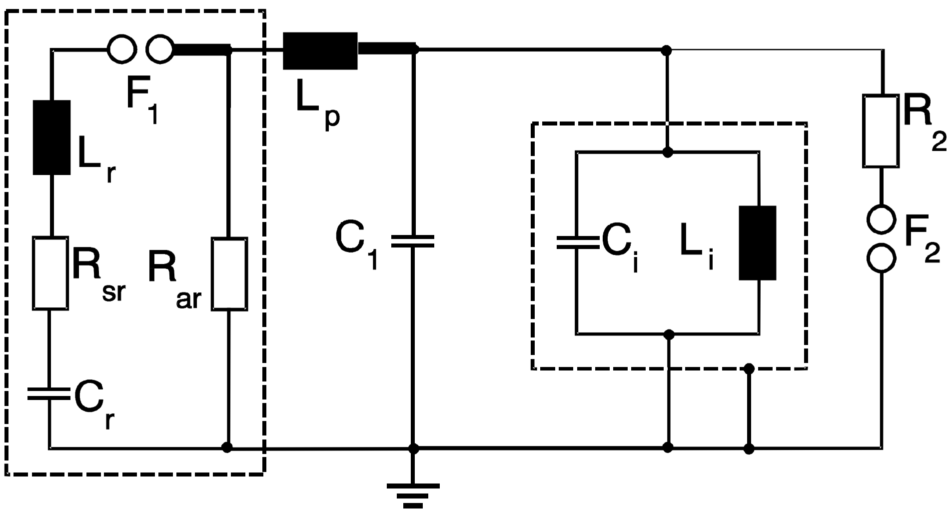


The impulse generator design is based on the Marx circuit. The basic circuit diagram is shown on Fig. 15-1. The impulse capacitors C_s (12 capacitors of 750 nF) are charged in parallel through the charging resistors R_c (45 kΩ) (highest permissible charging voltage 200 kV). When the charging voltage has reached the requider value, breakdown of the spark-gap F_1 is initiated by an external triggering pulse. When F_1 breaks down, the potential of the following stage (points B and C) rises. Because the series resistor R_s is of low ohmic value compared with the discharging resistor R_b (4.5 kΩ) and the charging resistor R_c, and since the low-ohmic resistor

R_a is separated from the circuit by the auxiliary spark-gap F_{a1}, the potential difference across the spark-gab F_2 rises considerably and the breakdown of F_2 is is initiated. Thus the spark-gaps are caused to break down in sequence. Concequently the capacitors are discharged in series-connection. The high-ohmic discharge resistors R_b are dimensioned for switching impulses and the low-ohmic resistors R_a for lightning impulses. The resistors R_a are connected in parallel with the resistors R_b, when the auxiliary spark-gaps break down, with a time dalay of a few hundred nanoseconds. This arrangement is necessary in order to secure the functioning of the generator.

The required voltage is obtained by selecting a suitable number of series-connected stages and by adjusting the charging voltage. In order to obtain the necessary disscharge energy parallel or series-parallall connections of the generator can be used. In these cases some of the capacitors are connected in parallel during the discharge.

Max. test voltage amplitudes: 2.1 MV lightning impulse. 1.6 MV switching impulse.



Test circuit

Fig. 15-2 Equivalent diagram of the impulse test circuit.
C_r resulting impulse capacitance, R_{sr} resulting series resistance, R_{ar} resulting discharge resistance, L_rL_p stray inductances, C_i input capacitance of transformer, L_i transformer inductance, C_1 capacitance of voltage divider, F_1 spark gaps of impulse generator, F_2 calibration spheregap, R_2 protective resistor.

The required impulse shape is obtained by selecting the series and discharge resistors of the generator suitably.

The front time can be calculated approximately from the equation:

(15.1) $T_1 \approx 2,5 * R_{sr} * (C_i + C_1)$

and the time to half value from the equation:

(15.2) $T_2 \approx k * \sqrt{L_i * C_r}$

The factor k depends on the quantities R_{sr}, R_{ar}, L_i and C_r.

In practice the testing circuit is dimensioned according to experience.

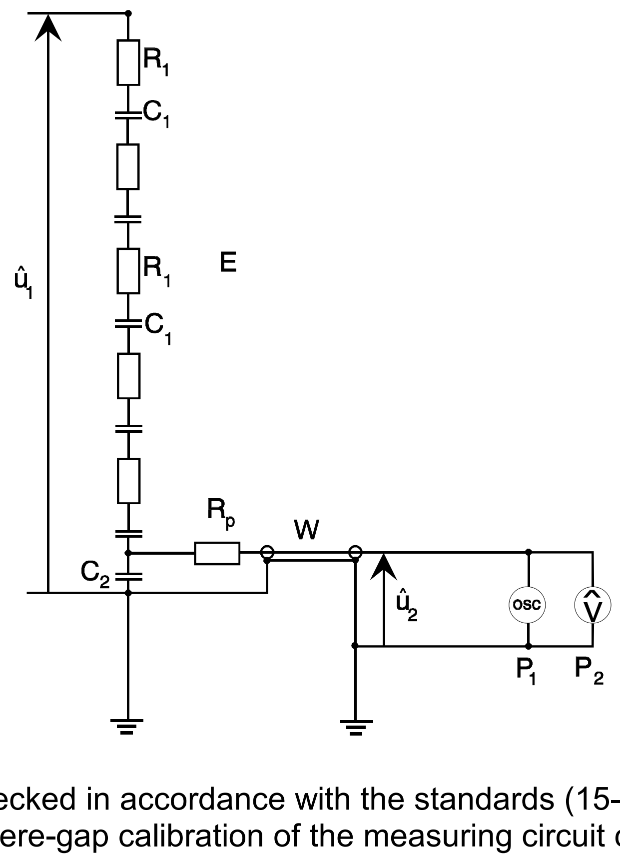
Voltage measuring circuit

The impulse shape and the peak value of the impulse voltage are measured by means of an oscilloscope and a peak voltmeter which are connected to the voltage divider (Fig. 15-3). The measuring range can be changed by short-circuiting part of the high voltage capacitors or changing the low voltage capacitor of the divider.

Fig. 15-3

The impulse voltage measuring circuit.

E damped capacitive voltage divider, W measuring cable (=wave impedance = R_p), P_1 oscilloscope, P_2 peak voltmeter, R_p terminal resistance of the measuring cable, R_1 damping resistor of voltage divider, C_1 high voltage capacitor of voltage divider, C_2 low voltage capacitor of divider.



The measuring circuit is checked in accordance with the standards (15-2) and (15.3). If necessary the sphere-gap calibration of the measuring circuit can be performed in connection with the testing according to the standard (15.4)

Transformer testing and fault detection connections

The lightning impulse test is normally applied to all windings. The impulse test-sequency is applied successively to each of the line terminals of the tested winding. The other line terminals and the neutral terminal are earthed (single-terminal test, Fig. 15-4a and b).

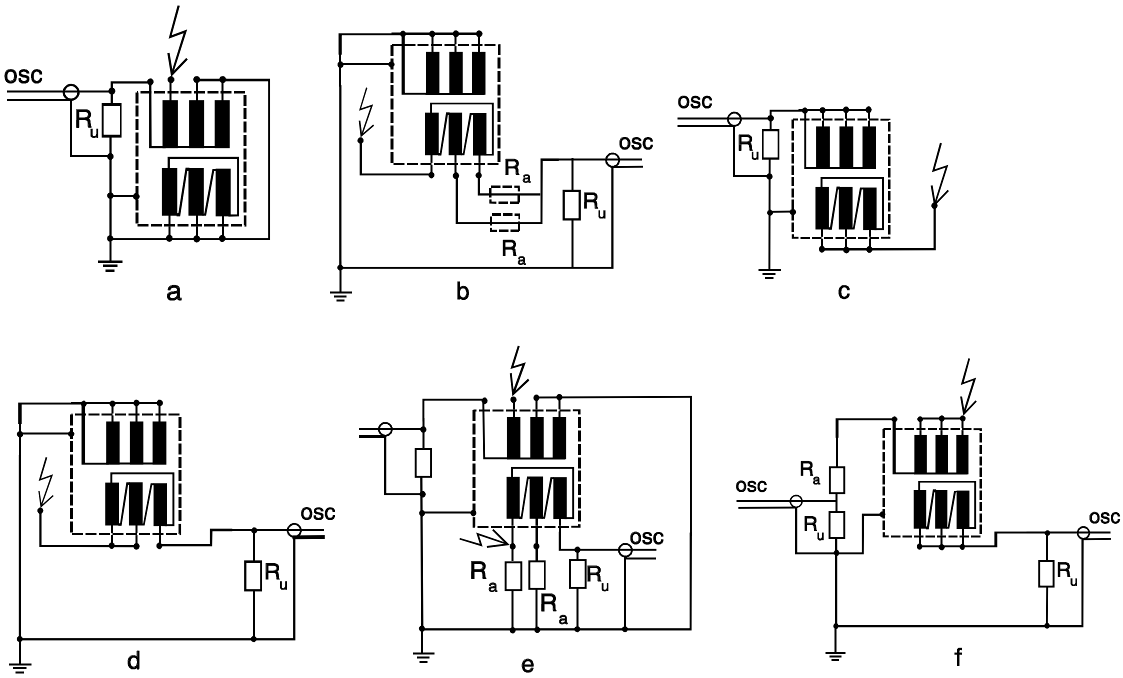


Fig. 15-4 Transormer impulse testing and fault detection connections.
a and b 1- terminal testing, c 3- terminal testing, d 2- terminal testing, e test with transferred voltages, f neutranl terminal testing.

When testing low voltage windings of high power the time to half-value obtained is often too short (Fig. 15-5). However, the time to half-value can be increased by connecting suitable resistors (R_a in Fig. 15-4b) between the adjacent terminals and earth. According to the standard IEC 76-3 the resistances of the resistors must be selected so that the voltages at the adjacent terminals do not exceed 75 % of the test voltage and the resistance does not exceed 500 Ω.

A delta-connected winding (and star-connected winding, unless the neutral is available) is also tested with an impulse test-sequence applied to the line terminals of the tested winding connected together, while the other windings are earthed (three-terminal test, Fig. 15-4c).

For delta-connected windings the single and three-terminal testings can be combined by applying the impulse to two line terminals at a time, while the other line terminals are earthed (two-terminal testing, Fig. 15-4d). In this case two phases are simultaneously tested in a single-terminal connection and one phase in a test connection corresponding to three-terminal testing.

The two- and three-terminal testings are not included in the standard (15.5), but they can be done if it is so agreed.

When the low voltage winding cannot in service be subjected to lighting overvoltages from the low voltage system (e.g. step-up transformers, tertiary windings) the low voltage winding may (by agreement between customer and manufackturer) be impulse tested simultaneously with the impulse tests on the high voltage winding with surges transferred from the high voltage winding to the low voltage winding (Fig. 15-4e, test with transferred voltages). According to IEC 76-3 the line terminals of the low voltage winding are connected to earth through resistances of such value (resistances R_a in Fig. 15-4e) that the amplitude of transferred impulse voltage between line terminal and earth or between different line terminals or across a phase winding will be as high as possible but not exceeding the rated impulse withstand voltage. The resistance shall not exceed 5000 Ω.

The neutral terminal is normally tested indirectly by connecting a high-ohmic resistor between the neutral and earth (voltage divider R_a, R_u) and by appluying the impulse (Fig. 15.4d) to the line terminals connected together. The impulse test of a neutral terminal is performed only if requested by the customer.

For fault detection in single-terminal and two-terminal tests the neutral of star-connected windings are earthed via a low-ohmic resistor (R_u). The current flowing through the detection resistor during the test is rocorded by means of an oscilloscope. Evidence of insultaion failure arising from the test would be given significant discrepacies between the calibration impulse application and the full voltage applications in recorded current wave-shapes. Certain types of faults give rise to discrepancies in the recorded voltage wave-shapes as well.

For fault detection in three-terminal tests and tests on the neutral terminal the adjacent winding is earthed through a low-ohmic resistor. The fault detection is then based on recording the capacitive current which is transferred to the adjacent winding.

Performance of the impulse test

The test is performerd with standard lightning impulses of negative polarity. The front time (T_1) and the time to half-value (T_2) are defined in accordance with the standard (15.4) (Fig. 15-5)

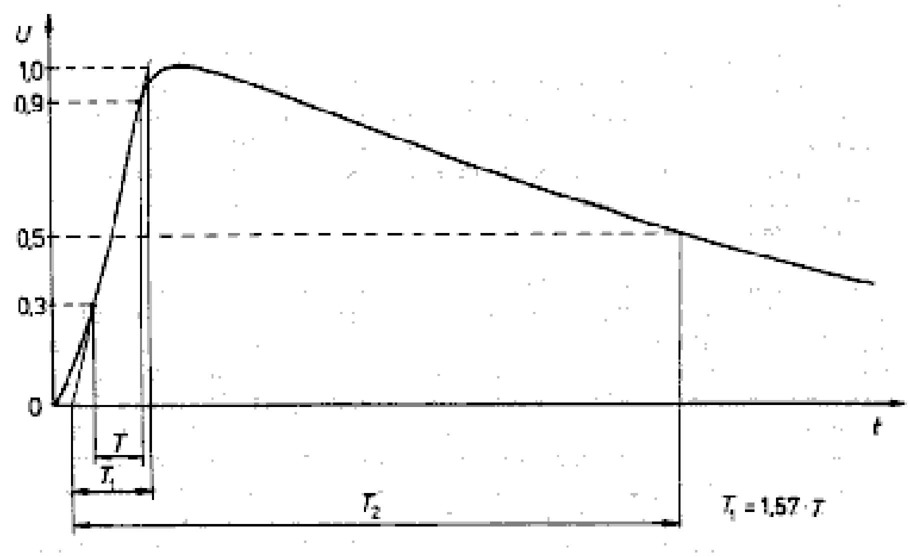


Fig. 15-5 Standard lightning impulse

Front time T_1 = 1.2 μs ± 30 %
Time to half-value T_2 = 50 μs ± 20 %

In practice the impulse shape may deviate from the standard impulse when testing low-voltage windings of high rated power and windings of high input capacitance.

The voltage measurement is based on the reading of the peak voltmeter. If required the voltage measuring system, including the peak voltmeter, is calibrated by means of sphere-gap, in connection with the testing of the first line teminal. In testing the other terminals the voltage measurement is based on the reading of the calibrated peak voltmeter. The voltage calibration is performed at 60 % of the voltage test level.

Oscillographic records are made of the applied voltage and the voltage across the fault detection resistor R_u during calibration at 62.5 % of the voltage test level and during the 100 % voltage applications.

At full test voltage each line terminal is tested with as many impulses as is required by the standard. In order to facilitate the detection of possible discrepacies in the oscillographic records, the oscilloscope attenuation is adjusted such that the curves recorded during the full wave applications can be brought to coincide with those obtained during the calibration.

Unless agreed otherwice different tappings are selected for the impulse tests on the three phases of a three-phase transformer, usually the two extreme tappings and the principal tapping.

Test report

The summary of test results is given on a form termed "Report of impulse voltage withstand test on transformer". The osccillographic record and measurement records are stored in the archives, where they are available when requider.

Literature

(15.1) IEC Publ. 60-3 (1976): High-voltage test techniques. Part 3: Measuring devices.

(15.2) IEC Publ. 60-4 (1977): High-voltage test techniques. Part 4: Application guide for measuring devices.

(15.3) IEC Publ. 52 (1960): Recommendations for voltage measurement by means of sphere gaps.

(15.4) IEC Publ. 60-2 (1973): High-voltage test techiques. Part 2: Test procerudes.

(15.5) IEC Publ. 76-3 (2000): Power transformers. Part 3: Insulation levels and dielectric tests.

10. PARTIAL DISCHARGE MEASUREMENT

Scope and objeck

A partial discharge in an insulating medium is a localized electrical discharge, which does not bridge the electrodes of the insulation structure. The field strenght of a weak part of the dielectric may exceed the dielectric streght, which causes a breakdown. It is, however, to be observed that the weak parts mentioned may form a small portion of the insulation structure only. The remaining whole insulating gap can, therefore, withstand voltage stresses corresponding even to the test voltage, and the breakdown remains partial. The ionic discharge following the test voltage, and the breakdown is called a partial disharge for the above mentioned reasons.

Resulting from a partial breakdown the voltage difference across the weak part of the dielectric decreases so much that the discharge current is interrupted. Due to the sinusoidal variation of the applied voltage the electrical field strenght increases again after the discharge has been extinguished. When the field strength reaches its critical value, a new discharge occurs. Thus discharges take place repeatedly.
(Fig. 18-1).

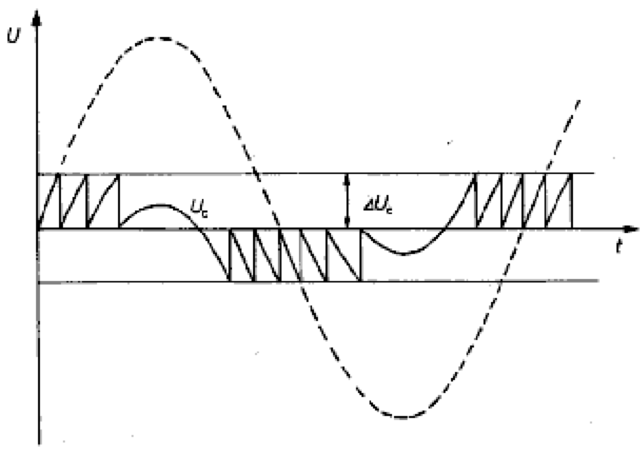


Fig. 18.1 Partial discharges in a gas-filled cavity.

ΔU_C voltage strenght across the cavity.

The situation is enlightened by the simple anologue circuit of a cavity (Fig. 18.2). C_a is the capacitance of the whole insulating gap, the spark-gap and the capacitrance C_C represent the cavity and the capacitance C_b represents thr dielectric in series with C_C.

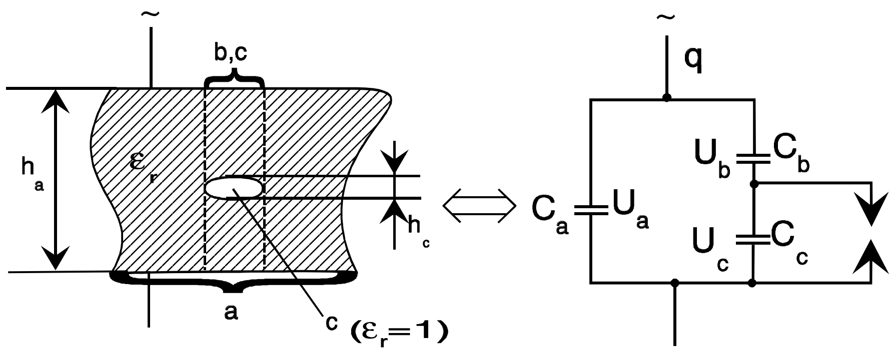
When the voltage U_C across C_C has increased enough, the spark-gap ignites. The capacitance C_C disharges and the voltage difference across the cavity vanishes within 1...1000 ns. The discharge magnitude or apparent charge q and the voltage U_C are related by the following equation:

(18.1) $q = C_b * U_c$

The discharge gives rise to a current pulse, which causes a fast voltage charge at the terminals of the transformer; this change can be measured by means of a capacitive voltage divider and a pulse transformer.

Fig. 18.2

Analogue circuit of a gas-filled cavity.



The partial discharges do not lead to an immediate breakdown. They have, however, other effects on the insulating medium:

- the surface of the dielectric is bombarded by iones. which cause temperature-rise and may result in degrading and chemical changes in the insulating material

- Chemical changes may give rise to material components, which speed up ageing. On the other hand the partial discharges may also be extinguished by the influence of some other degradation products

- disharges cause high local field strengths near the discharge site.

These phenomena result in degradation of the dielectric properties of the insulating medium, and increase of losses.

The object of the partial discharges measurement is to reveal the above mentioned weak parts of the dielectric, which may cause destruction of the transformer in service.

Measurement circuit

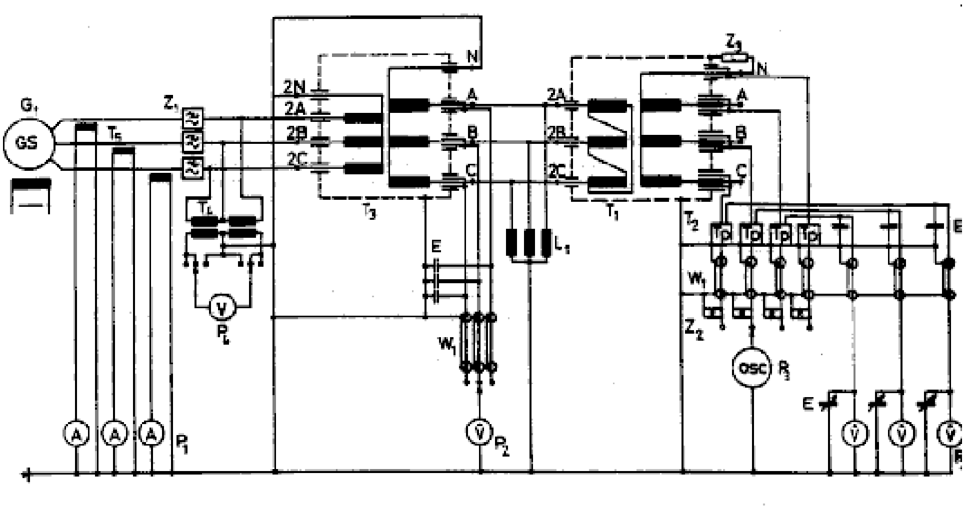


Fig. 18-4 Measurement of partial discharges.

G_1 feeding generator
T_1 transformer to be tested
T_2 pulse transformer
T_3 step up transformer
L_1 compensating reactors
Z_1 low-pass filters
Z_2 terminal resistors of measuring cable
P_3 oscilloscope
W_1 measuring cables
E capacitive voltage divider

P_1 ammeters
P_2 volt-meter (peak value)
P_4 volt-meter
Z_3 reactance

The feeding and measuring instruments used are described on a separate measuring instrument list (Section 20).

Performance of the measurement

The measurement is based on observing and evaluating the apparent charge in accordance with the standard (18.6) IEC 76-3. The measuring system is basically a wide-band system, but a narrow- and instrument can be connected to the system if necessary.

<u>Stability test</u>

Due to internal capacitances, the voltage on the high voltage side of the transformer under test may rise to an unacceptably high value when connecting the generator to the feeding circuit. For this reason the stability of the generator voltage control must be tested.

The stability is tested at a voltage equal to half the measurement voltage. Therefore, spark-gaps are connected between the high voltage terminals and earth. The spark- gaps are set according to the maximum permissable voltage of the transformers.

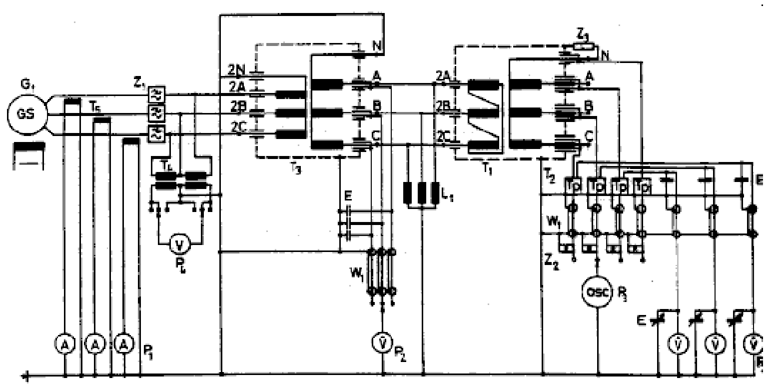
<u>Calibration measurement</u>

In the calibration measurement (Fig. 18-3) an apparent charge q_O is injected between each high voltage terminal and earth. The voltage pulse caused by the injected charge is measured by means of an oscillope with the aid of pulse transformers connected to the test to of the bushings. The reading on the oscilloscope corresponds to the charge q_O. The high-voltage side of the step-up transformer is earthed during this measurement.

<u>Fig. 18-3</u>

Calibration

C_1 calibration generator, which produces charge pulses of magnitude q_O



Partial discharge measurement

The voltage is increased stepwise, first up to the measuring voltage U_2, when the occurance of discharges is checked. The test voltage is increased to the pre-stress voltage level U_1 and held there for a duration of 5 seconds. The pre-stress voltage is applied in order to ignite the discharges. Thereafter, the voltage is rapidly reduced to U_2 and maintained at this value for the agreed duration of time t_{mes} (Fig. 18-5). During this period the occurence of discharges is being checked at the terminals of the transformer. If discharges occur, the results are recorded in order to determine the discharge magnitudes. If there are discharges at the voltage level U_2 the voltage is decreased stepwise after the duration of time T_{mes} in order to determine the extension voltage. The voltage measurement is carried out at the high voltage side of the transformer to be tested (Fig. 18-4).

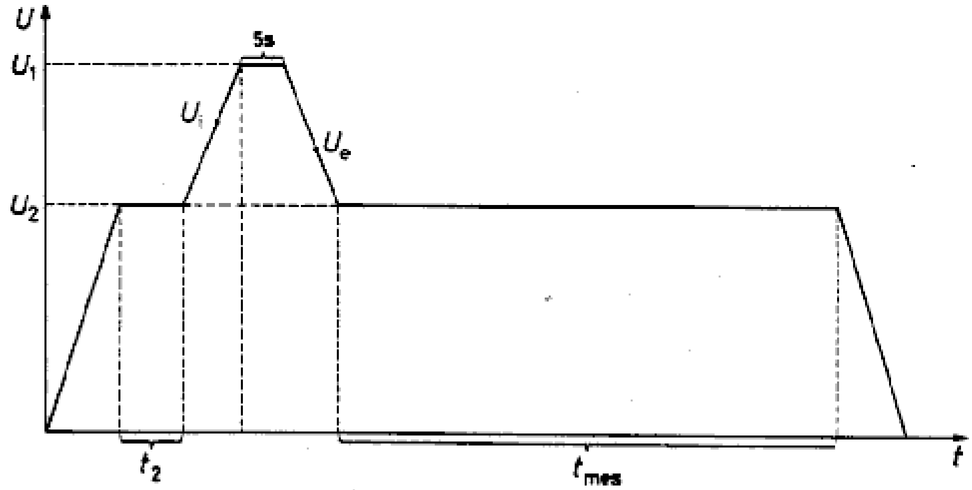


Fig. 18.5 Test voltge
U_1 pre-stress voltage
U_2 measuring voltage
U_i partial discharge inception voltage
U_e partial discharge extinction voltage

According to the standard (18.6) IEC 76-3 the test is carried out using the following values of test voltages between line and neutral terminals and test period durations:

- $U_1 = U_m$
- U_2 = either $1.3\, U_m/\sqrt{3}$ with $q < 300$ pC
  or $1.5\, U_m/\sqrt{3}$ with $q < 500$ pC
- t_2 = 5 min
- t_{mes} = 30 min

When the test is carried out as a special test, the test procedure can be separately agreed upon.

Test report

A summary of test results is put down on a form made for this purpose. The form is stored in the archives, and is then available when requasted.

Literature

(18.1) ELECTRA No. 19, November, 1971.
(18.2) ELECTRA No. 11, December, 1969.
(18.3) Brown, R.D., Corona measurement on high voltage apparatus using the bushing capacitance tap. IEEE Trans. Power Apparatus and Systems84 (1965), pp 667-671.
(18.4) Harrold, R.T. and Dakin, T.W., The relationship between the picocoulomb and microvolt for corona measurements on h.v. transformers and other apparatus.
IEEE Paper T 72086-2, 1972.
(18.5) IEC Publication 270, 1968. Partial discharge measurements.
(18.6) IEC Publ. 76-3 (1980): Power Transformers.
Part 3: Insulation levels and dielectric tests.

11. MEASUREMENT OF ZERO-SEQUENCE IMPEDANCE

Purpose of the measurement

The zero-cequence impedance is usually measured for all star-connected windings of the transformer. The measurement is carried out by supplying a current of rated frequency between the parallell connected phase terminals and the neutral terminal. The zero-sequence impedance per phase is three times the impedance measured in this way. The zero-sequence is needed for earth-fault protection and earth-fault current calculations.

Measuring circuit and performance of measurement

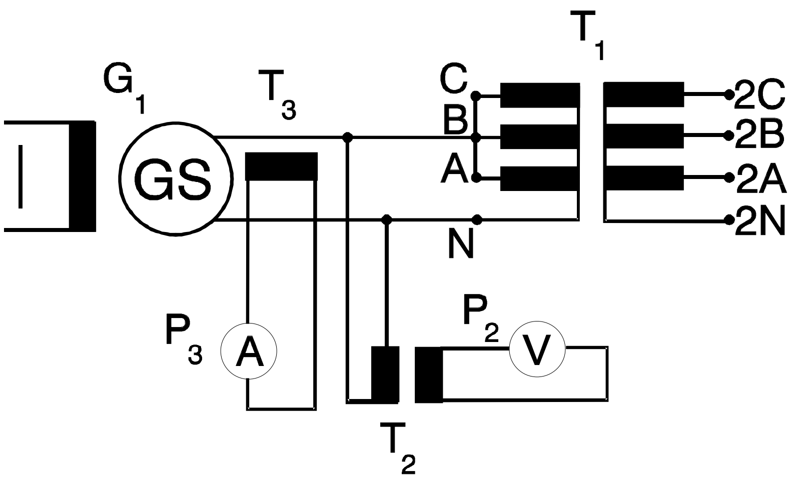


Fig. 9-1. Circuit for zero-sequence impedance measurement
G_1 supply generator, T_1 transformer to be tested, T_2 voltage transformer, T_3 current transformer, P_2 voltmeter, P_3 ammeter, I test current

The zero-sequence impedance is dependent on the current flowing through the winding. Usually the value corresponding to rated current I_N is stated. This implies that the measurement is carried out with a test current of 3 x I_N. However, this is not always possible in practice since the current must be limited to avoid excessive temperature of metallic constructional parts. The zero-sequence impedance is measured as function of test current, and when necessary the final result is obtained by extrapolation.

Result

The zero-sequence impedance is usually given as a percentage of the rated phase impedance. When the transformer has a three-limb core and no delta-connecter windings, the zero-sequence impedance is about 30...60 %. When the transformer has a delta-connected winding, the zero-sequence impedance is 0.8...1.0 times the corresponding short-circuit impedance.

In the test report the zero-sequence impedance values at the principal and extreme tappings are stated.

12. CAPACITANCE MEASUREMENT

Purpose of the measurement

The purpose of the measurement is to determine the capacitances between the windings and the earthed parts and between the different windings of the transformer.

The capacitance values are needed when planning transformer overvoltage protection and calculating the overvoltages affecting the transformer. In addition, the results are used by the manufacturer for design purposes.

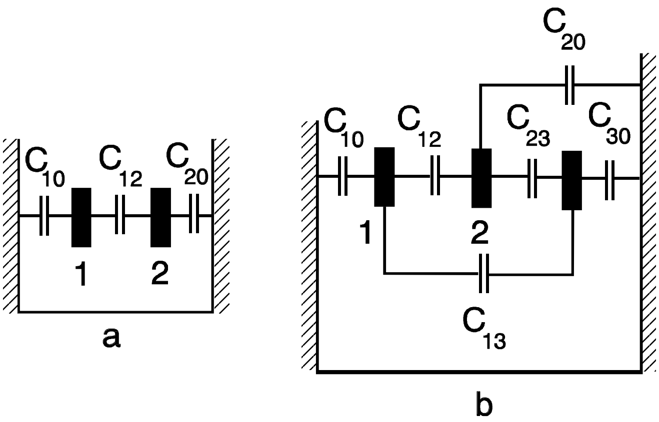
Performance of the measurement

All line terminals of each winding are connected together during the measurement. The winding capacitances of two- and three-winding transformers are shown on Fig. 10-1.

<u>Fig- 10-1</u>

Transformer capacitances.

a two-winding transformer
b three-winding transformer



Because the partial capacitances (C) in Fig. 10-1 cannot be measured separately, the values of resulting capacitances (K), obtained by combining the partial capacitances, are measured and the required partial capacitance values are calculated from the measured values. The measurement is carried out by means of a capacitance bridge.

A two-winding transformer is measured as follows:

- The capacitance K_{10} between earth and winding No 1 is measured, when winding No, 2 earthed.

(10.1) $K_{10} = C_{10} + C_{12}$

- The capacitance K_{20} between earth and winding No. 2 is measured, when winding No. 1 is earthed.

(10.2) $K_{20} = C_{20} + C_{12}$

- The capacitance K_{12} from the interconnected windings No. 1 and 2 to earth is mesured.

(10.3) $K_{12} = C_{10} + C_{20}$

The partial capacitances C_{10}, C_{12} and C_{20} are determined by solving the set of equations (10.1)...(10.3). For transformers with three or more windings a similar method is used. The number n_k of partial capacitances (and measurement combinations) is

(10.4) $$n_k = n * \frac{n+1}{2} \text{ kpl}$$

n = the number of windings

Test report

The partial capacitances are given per phase, thus three-phase capacitance values obtained in the measurement are divided by 3.

Literature

(10.1) Bertula T, Palva V: Transformer capacitances, Sähkö-Electricity in Finland 39 (1966) No. 10, p 289...293.

13. INSULATION RESISTANCE MEASUREMENT

Purpose of the measurement

The purpose of the measurement is to determine the leakage current reistance of the insultation. This is a function of the moisture and impurity contents of the insulation and of its temperature such that when these parameters are increased the insultaion resistance, as measured at a constant voltage difference across the insulation, depend on the strenght of the electric field during the measurement and thus on the size and construction of the transformer. This meaurement gives information about the condition of the insultation and secures that the leakage current is adequately small.

Performance of the measurement

The insulation resistance is measured by means of an insulation resistance meter at a voltage of 5000 V d.c. Each winding is measured separately by connecting the voltage between the winding to be tested and earth, while the other windings are earthed. The resistance readings R_{15} and R_{60} are taken 15 s and 60 s after connecting the voltage. The type of meter used, the measuring voltage, temperature, R_{15}, R_{60} and $\frac{R_{60}}{R_{15}}$ are stated in the report.

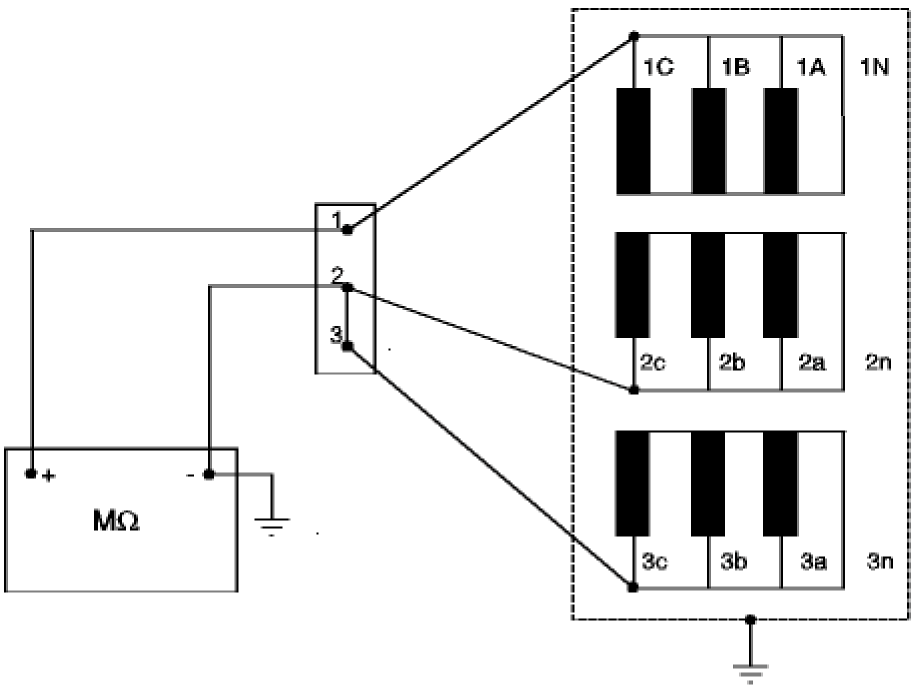


Fig. 11-1 Insulation resistance connection

14. LOSS FACTOR MEASUREMENT

Different electrical measurements can be carried out to check the condition of insultaions between transformer windings and between windings and earthed parts. The result (leakage current resistance) obtained in the insulation resistance measurement (compare item 11) describes in the first hand the behavior of insulation distances at direct current voltage. The leakage current resistance depends on the measuring voltage. The loss factor is primarily a characteristic quantity for the insulation itself, and therefore results obtained for transformers of different sizes cannot directly be compared to each other.

The loss factor measurement will be carried out by means of a special measuring bridge and a standard capacitor. The measuring voltage is usually 5 kV or 10 kV. The capacitance C_S of each winding and that of pair-wise connected windings and the loss factor tanδ against earth (connections as in item 10) are generally defined in the measurement.

Parallel-connection or series-connection (Fig. 12-1) can be used as the equivalent circuit of the insulation distance 1 to 2 to be measured.

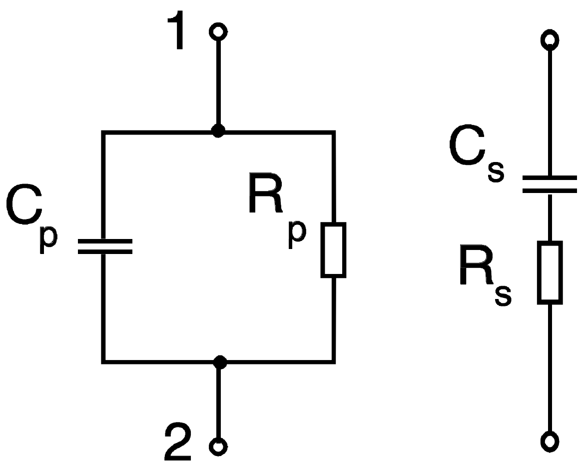


Fig. 12-1

Valid for the series-connection:

$\tan\delta = \omega * C_s * R_s$

$$R_s = \frac{\tan\delta}{\omega * C_s}$$

Obtained for the paralell connection

$$\tan\delta = \frac{1}{\omega * C_p * R_p}$$

$$R_p = \frac{1}{\omega * C_p * \tan\delta}$$

$$R_p = R_s * \frac{1+\tan^2\delta}{\tan^2\delta} \qquad C_p = \frac{C_s}{1+\tan^2\delta}$$

The loss factor tanδ is proportional to the effective resistance R_S of the insulation distance at the AC voltage.

The resistance depends on the dielectric losses of the insulation as well as on the leakage current component caused by the AC voltage. The loss factor tanδ can be used as a standard to be noted that the loss factor is the function of the insulation temperature and humidity content. The following equation distance to be measured.

$$P = U^2 * \omega * C_p * \tan \delta$$

The losses caused by the polarization generated in the insulation of the electrical field are proportional to the square of the voltage. Tanδ corresponding to these losses is independent of the voltage. If tanδ increases when the voltage is raised the reason for it may be that the leakage current resistance decreases (humidity, etc.) or discharges take place.

If a rounding electrode made of half-conducting material has been installed on top of the core, the electrode has an important effect on the size of the displacement angle. In such cases the tanδ-value does not correctly describe the condition of the insulation in this insulation distance.

Results

The insulation distances measured, the measuring voltages, the tanδ, capacitance and temperature of the insulation are stated in the report.

15. MEASUREMENT OF THE ELECTRIC STRENGHT OF THE INSULATING OIL

The electric strength of oil is given by the breakdown voltage, measured using an electrode system in accordance with IEC 156 (13.1). The electrodes are spherical surfaced with 25 mm radius and are 2.5 mm apart. The measurement is carried out at 50 Hz, the rate of increase of the voltage being 2 kV/s. The electric strenght is the average of six breakdown voltage values.

The electric strength of new treated oil should be at least 60 kV. Oil which does not withstand this voltage may contain air bubbles, dust or moisture.

In practice the breakdown voltage is about 70 kV.

Literature

(13.1) IEC 156 (1963) Method for the determination of the elctric strengh of insulating oils.

(13.1) IEC 296 (1982), Specification for unused mineral insulating oils for transformers and switchgear.

16. TEMPERATURE-RISE TEST

Purpose of the measurement

The purpose is to check that the temperature rises of the oil and windings do not exceed the limits agreed on or specified by the standards.

Apparatus

The supply and measuring facilities as well as the measuring circuit are the same as in load loss measurement (Section 4) and in the resistance measurement (Section 3). In addition thermometers are used for the measurement of the temperature of the oil, cooling medium and the ambient temperature and further a temperature recorder and Pt-100 resistive sensors are used for the measurement of certain temperatures and for equilibrium control.

Performance of the measurement

The test is performed by using the short-circuit method. The temperature rise of the windings is determined by the resistance method. The test is performed as follows:

Cold resistance measurement

The resistance and the corresponding oil temperature are measured. Resistances are measured between line terminals e.g., A-B and 2a-2b. The winding temperature is the same as the oil temperature.

Determination of the temperature rise of oil

The power to be supplied to the transformer is the sum of the no-load losses and load losses on the tapping on which the temperature-rise test is to be performed (generally the maximum loss tapping). With this power the transformer is warmed up to thermal equilibrium. The supply values and the temperatures of different points are recorded at suitable time intervals. The oil temperature rise above the cooling medium temperature can be calculated from the equilibrium temperatures.

Determination of the temperature rise of winding

Without interrupting the supply the current is reduced to rated current for 1 h. The supply values and the temperatures are recorded as above. When the current has been cut off the hot-resistance measurement is performed. The test connection is changed for carrying out the resistance measurement and after the inductive effects have disappeared the resistance-time-curves are measured for a suitable period of time (zero time is the instant of switching off the supply). The resistance is measured between the same line terminals as in the cold resistance measurement.

The resistance of the windings at shut-down are obtained by extrapolating the

resistance-time -curves to the instant of switching off. The temperature rises of the windings above the oil temperature are calculated on the basis of the "hot" and "cold" resistance values and the oil temperature. The temperature rises of the windings above the cooling medium temperature are found by adding the temperature rise of oil above the cooling medium temperature to the before mentioned winding temperature rises.

For multi-winding transformers the latter part of the temperature rise test is generally carrier out several times in order to determine the individual winding temperature rises at the specified loading combination.

For air-cooled transformers with natural air circulation the temperature of the cooling medium is the sama as the ambient temperature. The ambient temperature is measured by means of at least three thermometers, which are placed at different points around the transformer at a distance defined by the standards approximately half-way up the transformer. For forced-air cooled transformers the temperature of the ingoing air is measured. If water is used as cooling medium, the water temperature at the intake of the cooler is the reference temperatur.

The top oil temperature is measured by a thermometer placed in an oil-filled thermometer pocket on the cover or in the tube leading to the coolers. If transformer has separate cooler. the top oil temperature is measured from the tube leading to the cooler near the transformer. Furthermore the temperatures of the oil coming from or going to the transformer are measured and also some other temperatures which may by interesting.

The readings of the thermometers mounted on the transformer are checked in connection with the temperature rise test. and the power taken by the oil pump and fan motros is measured.

Results

The temperature rises are calculated as follows:

<u>Oil temperature rise</u>

The tempeerature rise of tpo oil Θ_{to} is

(14.1) $$\theta_{to} = \left(\frac{P_N}{P_t}\right)^x * (\vartheta_{to} - \vartheta_a)$$

P_N = rated losses P_k 75 °C + P_o
P_t = power supplied during the test
x = exponent according to the standard
ϑ_{to}= top oil temperature
ϑ_a = cooling medium temperature

The average temperature rise Θ_o of the oil is

(14.2) $$\theta_o = \left(\frac{P_N}{P_t}\right)^x * (\vartheta_{to} - \frac{\vartheta_2 - \vartheta_3}{2} - \vartheta_a)$$

ϑ_2 = temperature of oil going into the cooled
ϑ_3 = temperature of oil coming from the cooler

<u>Temperature rise of windings</u>

The average temperature of oil ϑ_o before the hot-resistance measurement is

(14.3) $$\vartheta_o = \vartheta_{to} - \frac{\vartheta_2 - \vartheta_3}{2}$$

The average temperature of winding ϑ_r is

(14.4) $$\vartheta_r = \frac{R_2}{R_1} * (\vartheta_s + \vartheta_1) - \vartheta_s$$

ϑ_s = 235 °C for Copper
ϑ_s = 225 °C for Aluminium
R_1 = cold resistance
R^2 = hot resistance
ϑ_1 = the average temperature of oil during cold resistance measurement

The average temperature rise Θ_{ro} of the winding above the oil temperature is

(14.5) $$\theta_{ro} = \left(\frac{I_N}{I_t}\right)^y * (\vartheta_r - \vartheta_o)$$

I_N = rated current of the winding
I_t = test current
y = exponent according to the standard

The average temperature rise Θ_r of the winding above the ambient termperature is

(14.6) $\Theta_r = \Theta_o + \Theta_{ro}$

The temperature rise Θ_{hs} of the hot spot of the winding above the ambient temperature is

(14.7) $\Theta_{hs} = \Theta_{to} + 1.1\ \Theta_{ro}$

The winding temperature insicator, if any, will be adjusted on the basis of the temperature risse Θ_{hs}

Results

The report indicates

- cold resistance values and the corresponding oil temperature
- temperatures of oil and cooling medium in thermal equilibrium and the corresponding losses
- hot resistances at shut-down and the corresponding currents
- temperature rises calculated from the measuring results

In addition information on the winding combination or combinations involved in the test, the tapping position, the cooling method and the time of delay is given.

Literature

(14.1) Kiiskinen, E.: Determining the temperature rise in a transformer winding using the resistance method. Sähkö-Electricity in Finland 47 (1974), No 1.

17. TEST WITH LIGHTNING IMPULSE CHOPPED ON THE TAIL

Purpose of the test

The purpose of the chopped lightning impulse test is to secure that the transformer insulations withstand the voltage stresses caused by chopped lightning impulse, which may occur in service.

Testing equipment

For the lightning impulse test the same testing and measuring equipment and the same testing and fault detection connections are used as for the standard lightning impulse test. The impulse is chopped by means of a triggered-type chopping gap connected to the terminal to which the impulse is applied. The delay of the chopping-gap ignition impulse in relation to the ignition of the impulse generator is adjustable, thus the time T_C from the start of the impulse to the chopping can be ajadjusted (Fig. 16-1).

Performance of the test

The test is performed with impulses of negative polarity. The duration T_C from the beginning of the impulse to the chopping can vary within the range of 2...6 μs (Fig. 16-1). According to the standard (16.1) the amout of overswing to opposite polarity shall be limited to not more than 30 % of the amplitude of the chopped impulse (Fig. 16-1). If necessary the overswing amplitude will be limited to the value montioned by means of a damping resistor inserted in the chopping circuit.

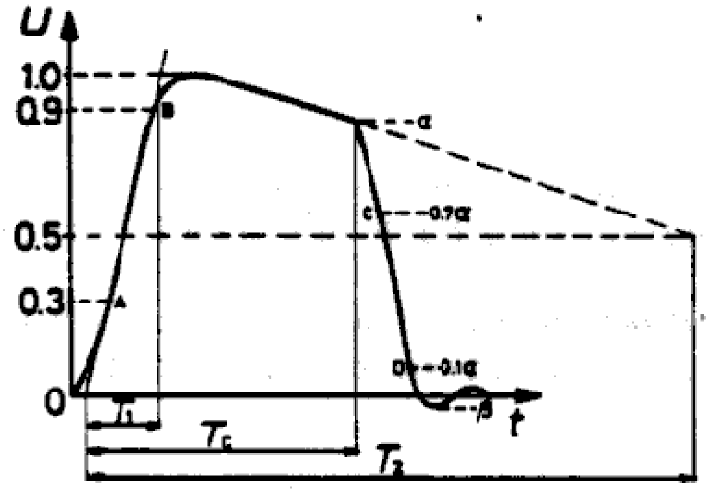


Fig. 16-1 Chopped lightning impulse.

T_1 = 1.2 μs ± 30 %

(T_2 = 50 μs ± 20 %)

$$y_c = \frac{\beta}{\alpha} * 100\% < 30\%$$

T_C = 2...6 μs

The voltage measurement is based on the peak voltmeter indication. If necessary the voltage measuring sircuit can be calibrated with the aid of a sphere-gap.

The test with chopped lightning impulse is combined with the test carried out with standard impulse.

The following order of pulse applications is recommended by the standard (16.1)

- one 62.5 % full impulse
- one 100 % full impulse
- one or more 62.5 % chopped impulses
- two 100 % chopped impulses
- two 100 % full impulses

The fault detection is also for chopped impulses primarily based on the comparison of voltages and winding currents obtained at 62.5 % calibration voltages and 100 % test voltages.
In order to make the comparison of fault detection oscillograms obtaine at 100 % voltage are of one same size as calibration oscillograms obtained at 100 % voltage are of one same size as calibration oscillograms obtained at 62.5 % voltage. At chopped impulse the fault detection is additionally secured since the test sequence includes the application of two standard impulses after the applicaton of the chopped impulses. At high test voltages (> 750 kV) there is a ssmall delay in the ignitions of the chopping-gap, which causes differences in the fault detection and calibration oscillograms of voltages and winding currents. In this case the fault detection must be based primarily on the recordings obtained at the application of full impulses.

When carrying out the chopped-impulse test, unless otherwise agreed, different tappings are selected for the tests on the three phases of a three-phase transformer, usually the two extreme tappings and the principal tapping.

Test report

The test voltage values, impulse shapes, tappings and the number of impulses at different voltage levels are stated in the report.

The oscillographic records and measurement records are stored in the archives, where they are available when required.

Literature

(16.1) IEC Publ. 76-3 (2000): Power transformers,
Part 3: Insultation levels and dielectric tests.

18. SWITCHING IMPULSE TEST

Purpose of the test

The purposet of the switching impulse test is to secure that the insulations between windings, between windings and earth, between line terminals and earth and between different terminals withstand the switching overvoltages, which may occud in service.

Performance of the test

The same testing and measuring equipment as for the lightning impulse test are used here.

According to the standard (17.1) the switching impulse test is carried out on each line terminal of a three-phase winding in sequence. A single-phase no-load test connection is used in accordance with Fig. 17-1. The voltage developed between line terminals during the test is approximately 1.5 time the test voltage between line and neutral terminals.

The flux density in the magnetic circuit increases considerably during the test. When the core reaches saturation the winding impedance is drastically reduced and a chopping of the applied voltage takes place (Fig. 17-2). The time to saturation determines the duration of the switching impulse. Because the remanent flux can amount to even 70 to 80 % of the saturation flux, the initial remanence of the core has a great influence on the voltage duration. By introducing remanent flux of opposite polarity in relation to the flux caused by the switching impulse, the maximum possible switching impulse duration can be increased. The remanence of opposite polarity is introduced in the core by applying low voltage impulses of opposite polarity to the transformer before each full voltage test impulse.

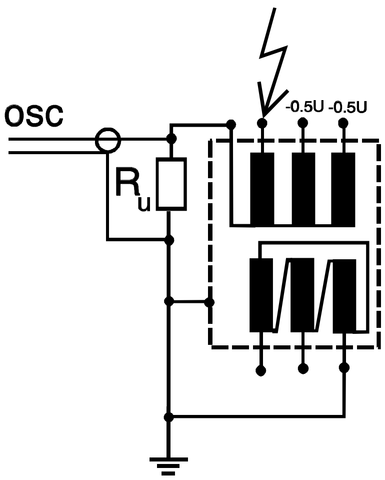


Fig. 17-1

Transformer switching impulse testing and fault detection connections.

The test is performed with impulses of negative polarity. The requirements on the switching impulse shape given in the standard IEC 76-3 are summarized in Fig.17-2.

The voltage measurement is based on the peak voltmeter indication. The voltage measuring circuit can be calibrated with the aid of a sphere-gap when required.

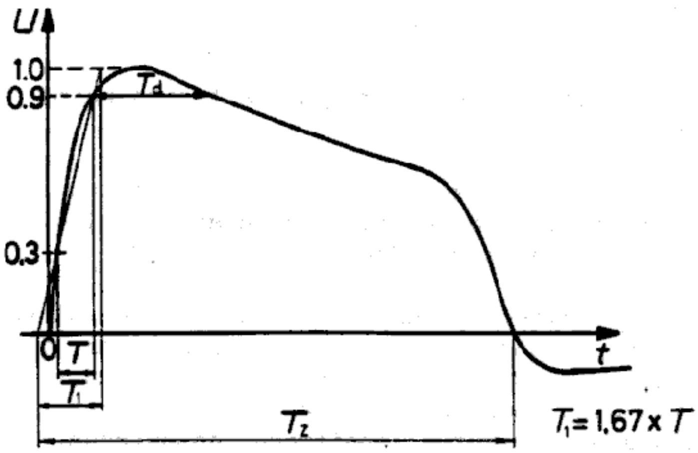


Fig. 17.2 Switching impulse

Front time T_1 > 20 µs
Time above 90 % T_d > 200 µs
Time to the first zero passage T_z > 500 µs

Calibration oscillograms of voltages and winding currents are recorded at 62.5 % voltage voltage level for comparison with the fault detection oscillograms recorded at 100 % voltage.

At full test voltage each phase will be tested with the number of impulses required by the relevant standard. In order to facilitate the comparison of oscillograms the oscilloscope will be attenuated so that the fault detection oscillograms are of the same size as the calibration oscillograms.

When comparing the fault detection and calibration oscillograms it is to be noticed that the magnetic saturation causes drastical reduction of voltage and increase in winding current and the time to saturation is dependent on the amplitude of the applied voltage. Thus voltage and current oscillograms obtained at full test voltage and at 62.5 % voltage level will deviate from each other in this respeckt.

In additon disturbances caused by corona discharges in the test circuit may be found on the current oscillograms recorded at test voltage.

The fault detection is mainly based on the voltage oscillograms. The test is successful if no sudden collapse of voltage caused by flashover or breakdown is indicated on the voltage oscillograms and no abnormal sound effects are observed.
When the core reaches saturation a slight noise caused by magnetostriction can be heard from the transformer.

Test report

The test voltage values. impulse shapes, and number of impulses at different voltage levels are stated in the report. The oscillographic records are stored in the archives, where they are available when required.

Literature

(17.1) IEC Publ. 76-3 (1980): Power transformers.
Part 3: Insulation levels and dielectric tests.

19. MEASUREMENT OF ACOUSTIC SOUND LEVEL

Purpose of the measurment

The purpose of the sound level measurement is to check that the sound level of the transformer meets the specification requirements, i.e. requirements given in relevant standards, e.g. (19.1) or (19.2), or guarantee values given by the transformer manufacturer. A sound spectrum analysis is carried out for the transformer at the customer's request. The sound spectrum indicates the magnitude of sound components (measured at a given band-width) as a function of frequency.

Mesuring equipment

A precision sound level meter complying with standards (19.1), (19.2) and (19.3) is used in the sound level measurements. The measurements are performed using the weightning curve A. The sound spectrum analysis of the transformer is carried out by recording the sound band levels automatically as a function of frequency. This is done with the aid of an analyser, which is both mechanically and electrically connected to the recorder or with the aid of an octave filter set joined to the sound level meter.

The measuring equipment is described in a separate list of equipment (Section 20).

Performance of the measurement

The measurement is carried out at measuring positions located around the transformer as detailed in the standards (19.1), (19.2) and (19.3).
According to the standards (19.1) and (19.3) the microphone position in the vertical direction shall be on horizontal planes at one third and two thirds of one transformer tank height, when the height of the tank is equal to or greater than 2.5 m. When the tank height is less than 2.5 m, and when the measurement is carried out in accordance with the standard (19.2), the measuring plane is located at half the tank height. The microphone is directed perpendicularly against the surface of the transformer (the principal radiating surface).

Before and after the transformer sound level measurement the background noise level is measured. Preferably the background level should be at least 9 dB(A) below the measured combined sound level. If the difference is less than 9 dB(A) but not less than 3 dB(A), a correction for background level will be applied according to standards (19.1), (19.2) and (19.3).

The transformer will be located at the test site so that the free distance from the transformer to reflecting objects is sufficiently large.

The measurement is carried out at rated voltage and frequency.

Test report

The mean value will be calculated from the measurement results. Correctionss for background level and environmental correction are made to the mean value.

Literature

(19.1) NEMA Standards Publication No. TR 1-1980.
Transformers, regulators and reactors.

(19.2) VDE 0532, Teil 1/03.82.
Bestimmungen für Transformatoren und Drosselspulen.

(19.3) IEC Publication 551, 1976. Measurement of transformer and reactor sound levels.

20. LIST OF EQUIPMENT

Rotating machines

The most important characteristics of the machines are mentioned.

<u>Machinery 1.</u>

Two identical generators which can be connected in parallel, and a driving motor.

Generators:	S = 3 MVA U = 1400 - 808 - 700 - 404 V I = 1240 - 2140 - 2470 - 4290 A f = 50 Hz
Motor:	P = 850 kW, slip-ring motor

The rotational energy of the unit is 18.5 MWs. The starting time is 1...3 min. and stopping time (only friction losses) is about 25 min.

When the outdoor temperature is not higher than 0°C and forced air cooling is used, the generator may be loaded with 135 % current at 100 % voltage (excitation not more than 300 A) and the motor accordingly with 140 % active power.

In the no-load voltage or the generators the 5th harmonic is 0.9 % and the 7th 1.1%. In addition there are slot harmonics of the 29th and 31st order. These, however, have no effect on the results in transformer tests.

<u>Machinery 2.</u>

Generator:	S = 15 MVA U = 10.5/6.06 kV I = 825/1430 A f = 50 Hz
Motors:	P = 1.5 MW, slip-ring motor P = 1.7 MW, squirrel-cage motor

The rotational energy of the unit is 83 MWs. The starting time is about 1.5 min. and the stopping time (only friction losses) about 60 min. The unit can be run continuously only in star-connection (10.5 kV).

Machinery 3.

Generator: S = 400 kVA
U = 1400 - 808 - 700 - 404 V
I = 165 - 286 - 300 -572 A
f = 16 2/3, 50, 60 and 83 Hz

Thermal loading capacity 485 kVA (not for 16 2/3 Hz frequency)

Motors: P = 260 kW, slip-ring motor + gear
P = 250 kW, squirrel-cage motor

The unit is used in two different ways. When it is used as 16 2/3, 50 or 60 Hz voltage source, the slip-ring motor acts as a drive-motor and the generator supplies the voltage. When the unit is used as a frequency converter the squirrel cage motor acts as a drive-motor and the generator supplies 83 Hz voltage. This voltage is connected to the rotor of the slip-ring motor and the stator then supplies 166 Hz voltage. The relation of gearing must be 1:1.

In the no-load voltage of the generator the 7th harmonic is 1 % and the 19th 0.7 %. At sinusoidal loading current these values do not increase notably. When using the frequency converter these harmonics are 2 %.

Machinery 4.

Generator: S = 300 kVA
U = 1400 - 808 - 700 - 404 V
I = 124 - 214 - 247 - 429 A
f = 50 Hz

Thermal loading capacity 450 kVA.

Motor: P = 300 kW, synchronous motor

The voltage curve of the generator contains the following harmonics: 5th harmonic 1.2 % and the 7th harmonic 1.0 %.

Machinery 5.

Generator: S = 1.5 MVS, 10 min.
U = 1.4 - 2.42 - 2.8 - 4.84 kV
I = 620 - 358 - 310 - 179 A
f = 250 Hz

Motor: 870 kW, 1 min/460 kW, 10 min. synchronous motor
The unit is mainly used for voltage testing

Machinery 6.

Generator: S = 10 MVA
U = 12 - 6.93 - 6 - 3.46 kV
I = 481 - 833 - 962 - 1667 A
f < 60 Hz

Motor: P = 1500 kW, squirrel cage motor.
The speed of rotation can be regulated by means of an inverter,

The rotational energy of the unit is 21.4 MWs at a speed corrensponding to 50 Hz.

Step-up transformers

Tecnical data:

Transformer 1.
S = 15 MVA continuously
U = 21 - 36.4 - 42 - 72.8 kV/3.03 - 5.25 - 6.06 - 10.5 kV
I = 412 - 238 - 206 - 119 A/2857 - 1650 - 1429 - 825 A
Z_k = 1.7 %

Current overload capability 40 %, 10 hrs.

When the transformer is used in connection with the 250 Hz generator, the highest permissible voltage is 116 kV. In short-duration single-phase voltage tests the voltage from terminal to earth must not exceed 100 kV.

Transformer 2.
S = 6 MVA continuously
U = 5000 - 8660 - 10000 - 17320 V/808 - 1400 V
I = 692 - 400 - 346 - 200 A/4920 - 2475 A

The transformer can be continuously overloaded by 15 % at a 35 °C ambient temperature and by 50 % when using three additional fans.

Transformer 3.
S = 2 MVA continuously
U = 20207 - 35000 - 40414 - 70000 V/808 - 1400 V
I = 57.2 - 33.0 - 28.6 - 16.5 A/1430 - 825 A

The insulations are dimensioned so that at 83 Hz, 166 Hz or 250 Hz the transformer voltage can exceed the rated value by about 30 % for a short period of time.

Transformer 4.

S = 5 MVA, 30 min.
U = 170/72 - 36/21 - 10.5 kV/1.4 (0.8) kV
i = 17/40 - 80/137 - 275/2060 (3570) A

The transformer is mainly used as step-up transformer for partial discharge measurement.

Transformer 5.

S = 15 MVA continuosly
U = 12/28 - 48.5 - 56 - 97 kV
I = 722/309 - 179 - 155 - 89 A
f = 50 and 60 Hz

Transformer 6.

S = 15 MVA continuously
U = 12000/1400 - 808 - 700 - 404 V
I = 722/6190 - 10720 - 12370 - 21440 A
f = 50 and 60 Hz

Capacitor bank

The bank comprises 864 units, the rated values of which are:

Q = 250 kVAr (50 Hz)
U = 7300 V
C = 15.4 μF

The rated power of the bank is 216 MVAr. The capacitors are so grouped that the reequired connection is obtained easily. Star and delta connections of the capacitors are possible. It is also possible to connect the capasitors for series-compensation.

The capacitors can also be used at 60 Hz.

Instrument transformers

Current transformers.

5 pc 4000 - 2000 - 1000 - 800 - 400 - 200 - 100 - 50 - 25 - 12.5 - 5 - 2.5 - 1.25/5 A, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz, 72.5 kV
Manufacturer: AEG

3 pc 800 - 400 - 200/5 A, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz, 20 kV
Manufacturer: Strömberg

3 pc 200 - 100 - 50/5 A, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz, 20 kV
Manufacturer: Strömberg

3 pc 50 - 25 -12.5 - 5 - 2.5 -1.5/5 A,15 VA cosφ=0.8, Cl. 0.2, 50 Hz,45 kV
Manufacturer: Strömberg

Voltage transformers

5 pc 45 - 20 - 10 - 5- 3 kV 100 V, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz,
insulation level 72.5 kV
Manufacturer: AEG

3 pc 35000/100 V, 15 VA, cosφ = 0.8, Cl. 0.2, 50 Hz
Manufacturer: Strömberg

3 pc 20000/100 V, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz
Manufacturer: Strömberg

3 pc 10000 - 5000/100 V, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz
Manufacturer: Strömberg

3 pc 3000 - 1500/100 V, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz
Manufacturer: Strömberg

3 pc 1500 - 750 - 380/100 V, 15 VA cosφ = 0.8, Cl. 0.2, 50 Hz
Manufacturer: Strömberg

The errors of the instrument transformers have been measured with burdens corresponding to actual conditions. The corrections for loss measurements are performed using these error curves.

Meters.

The following meters are available:

Meter	Accuracy class	Manufacturer
Voltmeters (r.m.s. value)	0.1	H & B
Voltmeters (1.11 x mean value)	0.2	Keithley
Ammeters	0.1	H & B
Wattmeters	0.2 $\cos\varphi_m = 1$	H & B
Wattmeters	0.5 $\cos\varphi_m = 0.1$	H & B
D.C. meteers	0.2	Siemens
Digital thermometer Pt-100 sensors, 12 Channels	± 0.1 °C	Systemteknik
Frequency meter	0.1	Bernecker + Rainer
Insulation resistance meter, max. 5000 V	2.5	Norma
Capacitance meter	0.3 %	ESI
Lossfactor capacitance bridge	< ± 0.1 % $\tan\delta \pm 1...2x10^{-4}$	TETTEX

Thermocamera equipment

AGA Thermovision 782
Scanner AGA Ttermovision 780
Sensitivity district 3 - 5,65 micron
temperature district -20 °C...+800 °C (min)
Polaroid-camera
Video tape recorder
Colormonitor

The resistance measuring apparatus

Transformer test system Tettex type 2285

Measuring range	1 μΩ … 500 Ω
Resolution	0,1 μΩ
Accuracy	± 0,06 % rdg ± 1 μΩ

Impulse testing apparatus

Impulse generator, Haefely

Number of stages	n = 12
Max. stage charging voltage	U_1 = 200 kV
Max. total charging voltage	ΣU_1 = 2400 kV
Max energy per stage	W_k = 15 kJ
Max. total energy	ΣW = 180 kJ
Capacitance per stage	C = 750 nF

Voltage divider, Haefely

Damped capacitive voltage divider
Voltage ranges for impulse voltage û = 50 kV...2400 kV
Capacitance C = 600 pF...2400 pF

The response characteristics and voltage ration of the voltage divider are checked in accordance with the standard IEC 60-3.

Peak voltmeter, Haefely Mod. 62

The instrument is provided with a digital display unit.

Accuracy: ± 1% for full wave measurements, when the duration of the wave front is between 0.2...450 μs and the time to half-value is <3000μs.
Accuracy for chopped-wave measurements:
± 1 % when chopping occurs on the wave tail
- 2 % when the time to chopping is between 0.5 μs and time to crest.
-3 % when time to chopping is 0.2...0.5 μs.

Calibration sphere gaps

Sphere-gaps with sphere diameters of 500 mm and 1000 mm are available. The 1000 mm sphere-gap is provided with a triggering electrode, and it can be used as a controlled chopping cap.

Sound level measuring equipment

Precision sound level meter, Brüel & Kjaer, 2215
Microphone, Brüel & Kjaer, 4190
Calibrator, Brüel & Kjaer, 4231